ON THE VARIATION OF A.C. PERMEABILITY OF TRANSFORMER SHEET STEELS WITH C. MAGNETIZATION

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Plate IX

ABSTRACT. An experimental study of the variation of A.C. permeability of transformer sheet steels with D.C. magnetization is reported. The experiments indicate that the inverse of the A.C permeability varies almost linearly with the D.C. magnetization. Oscillographic study of the hysteresis loops shows that they are always symmetrical and the tips of the loops bent in the direction of the H-axis. The bending of the tips increases with D.C. magnetization. The implications of the measurements are the following :—

(1) The admittance of an iron-cored reactor without air-gap increases linearly with D.C. magnetization.

(2) The current passed by such a reactor always contains appreciable amounts of odd harmonics.

INTRODUCTION

While studying the variation of the reactance of certain saturable core transformer, it was noticed that the current passed by the A.C. coils, with constant † A.C. voltage impressed on them varies linearly with the current passed through the D.C. coil. Since the current through a reactor is given by the expression

$$I=\frac{E}{Z}\simeq\frac{E}{X}$$

$$=\frac{E}{pL}$$

$$=\frac{E}{p.4\pi n^2 Al\mu.10^{-9}} \quad \ldots \quad (1)$$

the resistance of the coil being small in comparison to the reactance

where I = A.C. current.

E = A.C. voltage impressed on the coil.

$p=2\pi f$, f = frequency of A.C.

$n=N/l$, N being the total number of turns in the A.C. winding.

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† Constant amplitude.

A = Area of cross section of the limbs carrying the A.C. magnetic flux.

l = Length of A.C. flux path.

μ = A.C. permeability of the core material.

It is to be concluded that $1/\mu$ varies linearly with the D.C. current. The constant A.C voltage (E) on the coils, keeps the core magnetized at a constant A.C. flux density (B) given by the expression,

$$E = N.\,B\,A\,f\,4.44.\,10^{-8} \quad \ldots \quad (2)$$

The D.C. magnetization is proportional to the current in the D.C. coil. The expression connecting the magnetomotive force H with the current flowing through the D.C. coil being

$$H = \frac{4\pi N' i}{l'.10} \text{ oersteds} \quad \ldots \quad (3)$$

where N' = number of turns in the D.C. coil.

i = D.C. current in amperes.

l' = length of D.C. flux path.

The observation that the A.C. current varies linearly with the D.C. current therefore points to the following conclusion :

The inverse of the A.C. permeability at constant A.C. flux density varies linearly with the D.C. magnetization

A knowledge of the variation of A C. permeability with D C. magnetization is necessary in order to make designs of reactors or transformers that must carry a D.C current. The above mentioned observation shows that a simple relation may exist between the A.C. permeability and D.C. magnetization. The importance of such a relation inspired the author to undertake a series of measurements on several samples of transformer sheets (Stalloy) over a wide range of D.C. magnetization and A.C. flux-density. These are reported in this paper It will be observed that the relation is approximate. Nevertheless the approximation considerably simplifies the design problem and leads to designs close enough to the specified values to be of practical and commercial utility.

EXPERIMENTAL ARRANGEMENTS

The experimental arrangements used for obtaining data reported herein are represented in Fig. 1.—

The 110 volt winding of the 220V : 110V transformer T_2 applies a constant A.C. voltage across the winding S containing the sample. The number of turns in the winding is known. The A.C. current flowing through the winding is registered by the current ranges of an Avometer—a rectifier type A.C. current meter fed through a current transformer. The anode current

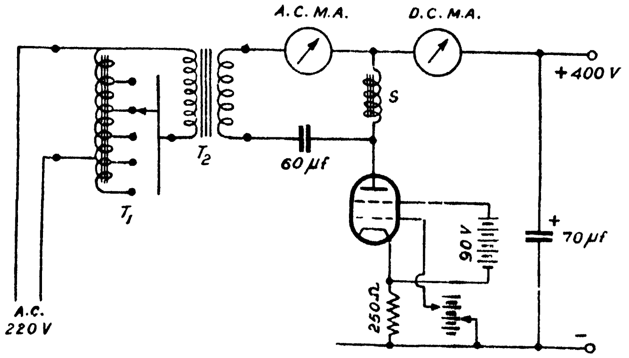

FIG. 1

Experimental arrangement for plotting the A.C. permeability vs D.C. magnetization curves.

of the tetrode power tube (or power tubes) T produces the D.C. magnetization. This is adjusted by varying the grid bias of the tube T. This current is made to flow through the sample winding S. The 60 μf paper condenser blocks the alternative path through the 110 volt winding of T_2. The resistance of the transformer windings 5 ohms ; 12 ohms), the reactance of the 60 μf blocking condnser (50 ohms) and the resistance of the sample winding (20 to 200 ohms), are small compared to the reactance of the windings. These are neglected in the calculations which utilised Eq. (1), (2) and (3). The A.C. current passed by the tube T, because of the A.C. voltage impressed on it is negligible as the effective plate impedance* of the tube is very high ($\simeq$ Megohms). The current registered by the A.C. meter is only the current passed by the winding. The A.C. voltage applied across the sample winding may be adjusted to any value between 26 volts to 120 volts by means of the auto-transformer T_1. The A.C. flux-density B depends solely upon the A.C. voltage and is independent of the A.C. coil current. Hence the measurements refer to the condition of constant A.C. flux density. The A.C. flux-density may be varied over a range of 1000-8000 gauss. The D.C. magnetization is

* The plate impedance of the tube is of the order of 100 000 ohms The low screen voltage—90 volts only—assure this high plate impedance Besides, degeneration in the cathode resistance of 250 ohms increases it several times

There is little chance of the tube taking a measurable A.C current because of the fluctuating plate voltage. It cannot also generate an A.C. current because of "ripples" in the grid and screen supplies The battery supplies assure a complete freedom from "ripples" in these supplies and so the plate current

That the A.C. current taken by the tube is negligible is proved by the fact that the readings obtained are independent of the type of tube 6L6, 6V6, 6F6 or 6K6—and depends only on the D.C. current passed through it produced by the tubes T—a pair of 6L6's—taking a D.C. current from zero to 150 m.A., through the windings. This produced a D.C. magnetization up to 15 oersteds sufficient to reduce the A.C. permeability by ten times.

RESULTS OF MEASUREMENTS

Measurements were made on several samples of silicon steel transformer sheets. These formed the cores of some radio transformers of foreign and Indian manufacture. The samples investigated upon are believed to be essentially different from each other and come from different sources. Besides these transformer sheets, experiments were performed also on "black sheet" and a certain specimen of permalloy. This specimen of permalloy was supplied to us by an American manufacturer through the India Supply Mission. Its permeability is found to be unusually low, it was probably sent without heat treatment.

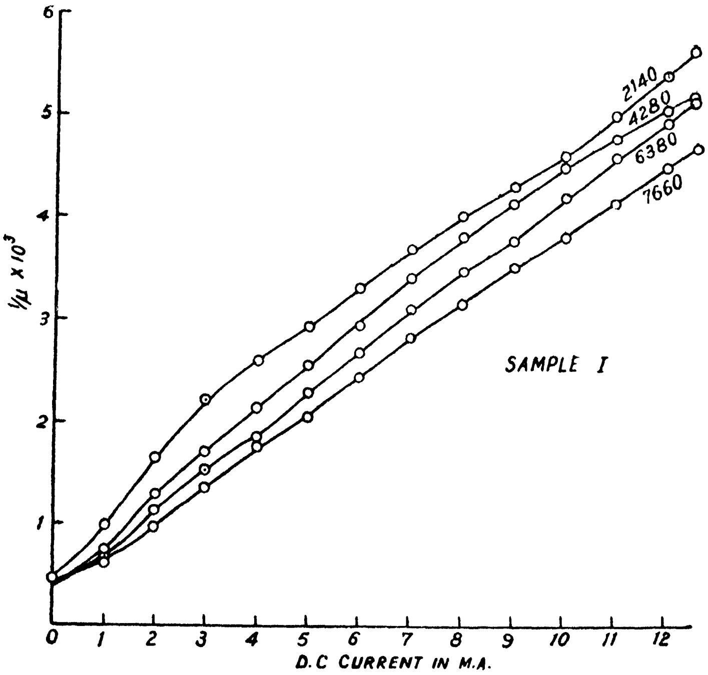

FIG. 2

A.C permeability vs D.C. magnetization curves for a sample I of silicon steel sheet

The sample experimented upon in Fig. 2 was in the form of a saturable core transformer of local construction. Details of this transformer may be obtained from the publication entitled "A circuit for the control of ionizing current by a saturable core transformer" (Banerjee and Mukherjee, 1947). The D.C. magnetization amounts to 1.7 oersteds per milliampere of D.C. current. The A.C. flux density in gauss is written down at the side of each curve.

The results of these measurements are represented in Figs 2,3, ... 9. It will be seen that the curves broadly verify the statement—"The inverse of the A.C. permeability at constant A.C. flux density varies linearly with the D.C. magnetization." It will also be seen that the slopes of the curves increase as the A.C. flux density diminishes—there being a greater change in A.C. permeability at low flux densities for a given change in the D.C. magnetization.

The departure from the straight line relation between the inverse of A.C, permeability and D.C. magnetization is more pronounced generally at low A.C. flux densities. It is evident from the curves that the exact relationship is quite complicated. So no attempt to formulate a mathematical expression which will take into account this departure from the simple relation will be made. A complicated mathematical expression is not of much help in simplifying the problem of practical designs.

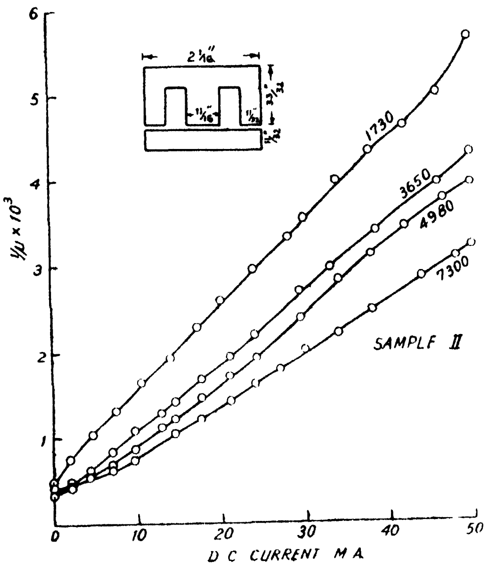

FIG. 3

Curves for sample II of silicon steel sheet

Details of Sample II are given below.

Thickness of core = 11/16″ inches; thickness of sheets = ·015″; number of turns in the winding, 2380 turns. The resistance of the winding is 200 ohms. The D.C. magnetization amounts to 0.285 oersteds per m.A. The number at the side of each curve indicates the A.C. flux-density in gauss for that curve.

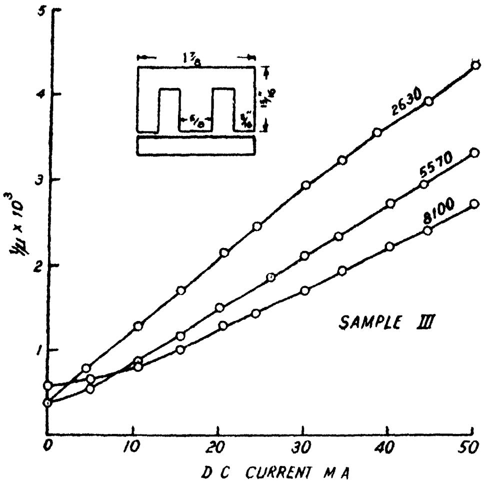

FIG. 4

Curves for sample III of silicon steel sheet

Details of Sample III are given below.

Thickness of core= $\frac{5}{8}''$; thickness of sheets= $.018''$; 2000 turns in the winding ; resistance=200 ohms. The D.C. magnetization amounts to 0.264 oersteds per m.A. The number at the side of the curve indicates the A.C. flux-density in gauss for that curve.

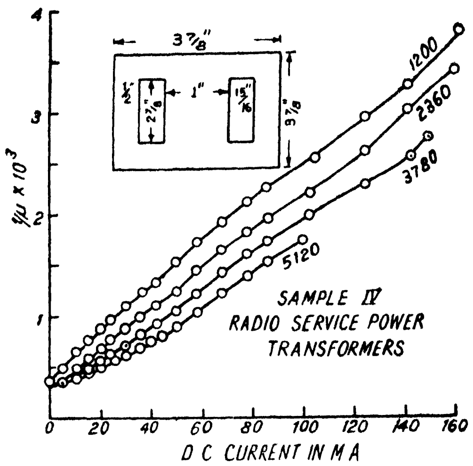

FIG. 5

Curves for sample IV "Stalloy" contained in a power transformer of Indian manufacture.

Details of Sample IV are given below.

Thickness of core= $1\frac{1}{2}$ inches ; thickness of sheets= $.015''$; 1100 turns in the winding ; resistance=18 ohms. The D.C. magnetization amounts to .056 oersteds per m.A. The numbers at the side of the curves indicate the A.C. flux-density in gauss.

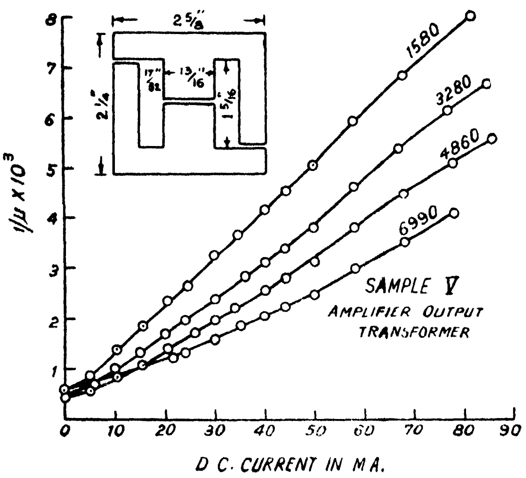

FIG. 6

Curves for sample V of silicon steel sheet.

Details of Sample V are given below.

Thickness of core $\frac{3}{4}''$; thickness of sheets $= .02''$; 2100 turns in the winding of 90 ohms resistance. The D.C. magnetization amounts to 0.195 oersteds per m.A. The numbers at the side of the curves indicate the A.C. flux-density in gauss.

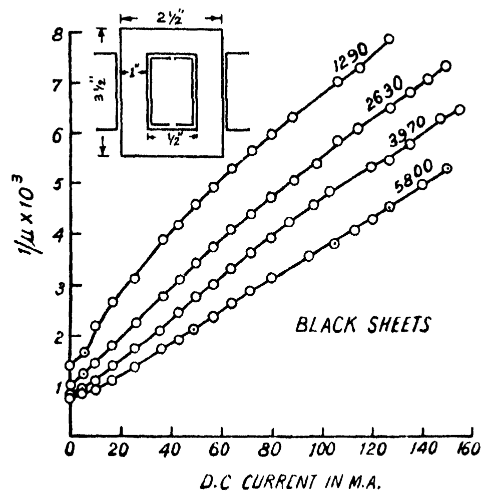

FIG. 7

Curves for a sample of "black-sheet"

Details of the Sample of ' black-sheet ' are given below.

Core thickness $= 1$ inch ; 32 sheets of $.02''$ thickness at each side. Two windings connected in series, each containing 1100 turns. Total resistance of the winding $= 130$ ohms. The D.C. magnetization amounts to 0.136 oersteds per m.A. The A.C. flux-density is written down at the side of each curve.

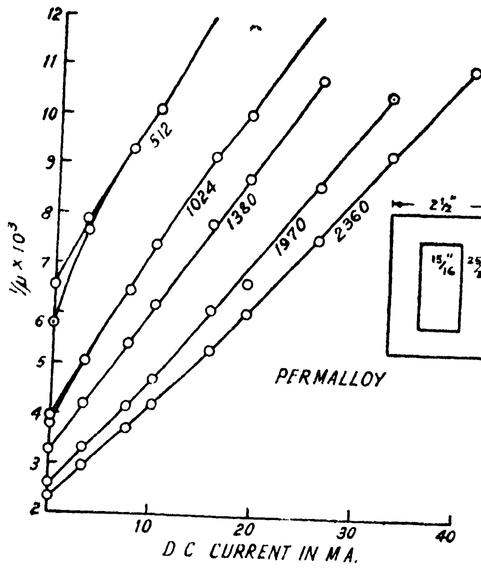

FIG. 8

Curves for a certain sample of what is supposed to be permalloy.

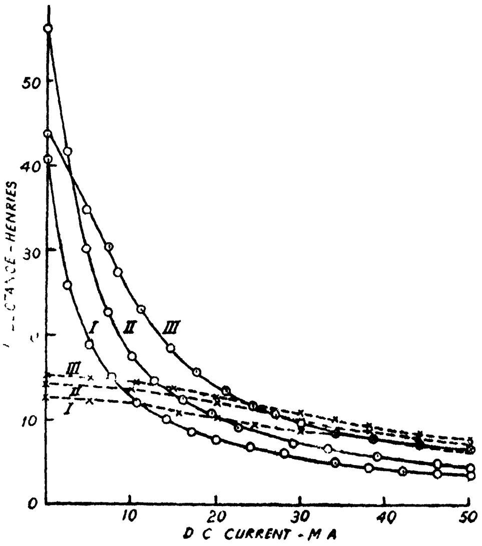

FIG. 9

Inductance vs. D.C current curves of sample II

The permalloy sample in Fig. 8 was obtained from an American manufacturer in the form of a sheet (.014″ thick, $2\frac{3}{4}''$ wide) of considerable length rolled into a circle. It was cut by metal shears and assembled into a core of the form shown in the figure. Care was taken in assembling the core such that the flux-lines were along the length of the sheets. Two windings were put on the two longer limbs each containing 3000 turns. The total resistance of the winding was 370 ohms. The D.C. magnetization amounts to 0.354 oersteds per m.A. As usual, the A.C. flux-density is written down at the side of each curve. The low permeability figures indicate that the permalloy sample was sent without the heat treatment

The full line curves represent the performance of the 2380 turn choke with no air gap in the core. The dotted line curves are for the same choke with a small air gap. It is to be seen that when there is a D.C. current flowing, introduction of an air gap sometimes increases the inductance. The air gap also greatly reduce the variation of inductance with D.C. current. Curves I correspond to an A.C. voltage of 26 volts on the winding and A.C. flux-density in the core of 1730 gauss ; curves II corresponds to an A.C. voltage of 55 volts on the winding and an A.C. flux-density of 3650 gauss ; curves III corresponds to an A.C. voltage of 110 volts and a flux-density of 7300 gauss.

Fig a B — 7300 gauss

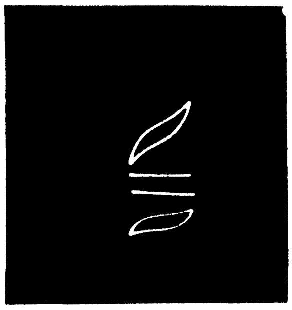

Fig b
B 3650 gauss

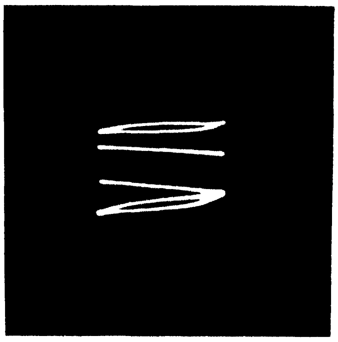

Fig. c B 1800 gauss

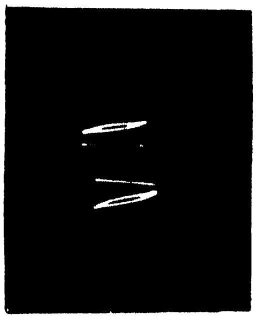

Fig. d B = 900 gauss

Oscillograms of hysteresis loops with and without D C magnetization obtained with sample No 2 The oscillograms were taken with a Cossor model 339J double beam oscillograph The straight line by the side of the curves is the trace of the second beam which gives the B axis The loop making a larger angle with the B axis is the one with D C. magnetization. Note that the tips of the loops are bent in the direction of H axis and that the bending persists even upto a flux density as small as 900 gauss

DISCUSSION ON THE METHOD OF MEASUREMENT

The measurements are essentially approximate and the author therefore does not claim precision. The errors arise from the following causes :—

(1) The equation utilised for the calculations assumes that the sample cores are uniformly magnetized throughout—they have a constant B and H everywhere. This is obviously not so with the samples utilised for the measurements.

(2) Equations (1) and (2) neglected the resistance of the sample winding and also the resistances and reactances of the transformer and the blocking condenser.

(3) The rectifier type A.C. milliammeter measures the average current and thereby limits the meaning of the measurements. A full understanding of the phenomenon is, however, not possible without the use of an oscillograph for studying the hysteresis loop or the waveform of the current.

The author did not adopt the 25 cm Epstein tests* recommended by the United States National Bureau of Standards. This testing method requires considerable quantities of sample material in the form of strips of 3 cm width and 28 cm length. As the sample materials were available to the author only in the form of cores of radio output and power transformers, he had to adopt the different arrangements of measurement as described here. The standard 25 cm Epstein test is superior to the method described here mainly in circumventing the effect of resistance of the windings. The arrangement described here is more suitable for rapid measurements with sample cores of small size in the range 1000-10,000 gauss induction with a D.C. magnetization.

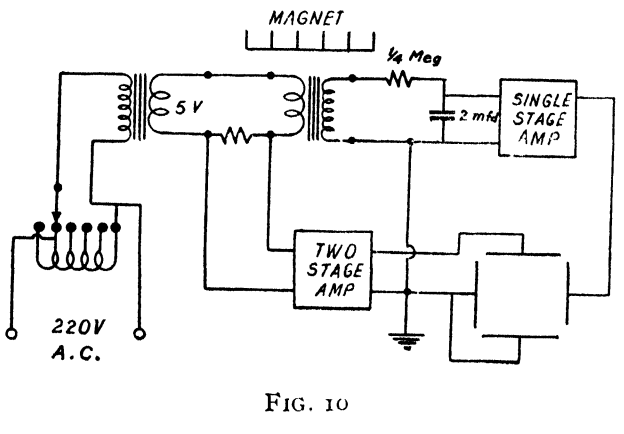

FIG. 10

Experimental arrangement for obtaining the hysteresis loops on an oscillograph.

* Sanford, R. L. Magnetic Testing, Circular of the National Bureau of Standards C 456.

OSCILLOGRAPHIC STUDY OF HYSTERESIS LOOPS

The experimental set up for an oscillographic study of the hysteresis loops with and without D.C. magnetization is indicated in Fig. 10. Sample No. 1—the saturable core transformer, sample No. 2—and sample No. 4 were subjected to this study. The saturable core transformer did not require the external magnet for D.C. magnetization which was effected simply by passing a D.C. current through the D.C. winding. With sample No. 4 D.C. magnetization was effected by passing a D.C. current through a third winding by means of a Pentode valve as in Fig. 1. Oscillograms of hysteresis loops for sample No. 2 are given in Plates IX A and IX B. They indicate the general nature of the phenomenon for silicon steels. The oscillograms were taken with a Cossor double beam oscillograph model 330A on Kodak blacktone bromide L 15 plates. The straight line by the side of each loop is the trace of the second beam of the double beam tube which automatically trace out a line parallel to the B-axis. The slope of the straight line connecting the tips of the hysteresis loops with this line gives a ready idea of the A.C. permeability.

A critical study of the oscillograms reveals the following facts :—

(1) The hysteresis loops are symmetrical whether they are with or without D.C. magnetization.

(2) The angle of inclination of the straight line joining the tips with the B-axis is greater with a D.C. magnetization and is independent of the direction of magnetization.

(3) Even for quite small values of A.C. magnetization the tips of the loops are appreciably bent towards the direction of the H-axis. This bending of the tips of the small hysteresis loops becomes more pronounced with a D.C. magnetization.

CONCLUSION

The results of the measurements show that the variation of A.C. permeability at constant A.C. flux-density with D.C. magnetization of silicon steel sheets follow more or less closely a law which may be enunciated as "The inverse of A.C. permeability at constant A.C. flux-density varies linearly with the D.C. magnetization." Further the magnitude of the A.C. permeability becomes smaller and the variation more rapid as the A.C. flux-density diminishes. The oscillographic study of the hysteresis loops gives the following informations :—

(1) The hysteresis loops are symmetrical and have greater inclination with the B-axis with a D.C. magnetization which is independent of the direction of magnetization.

(2) Even for quite small values of A.C. magnetization, the tips of the loops are visibly bent towards the direction of the H-axis and this bending of the tips of the hysteresis loops is more pronounced with a D.C. magnetization. This latter information differs from the impression that may be gathered from text-books* dealing with the subject. The figures drawn in these text-books give the impression that there is no bending of the tips of the small hysteresis loops. The appreciable bending of the tips of the hysteresis loops mean that the no-load current of a transformer or choke employing these silicon steel sheets contain appreciable amounts of odd harmonics, even when operating at a small A.C. flux-density and that the amount of these odd harmonics increases with D.C. magnetization.

A knowledge of the variation of A.C. permeability with D.C. magnetization is necessary in the design of chokes and transformers which must carry a D.C. current. Assumption of the simple relation of variation which has been established here will enable the designer of these apparatus to make paper designs more easily and quickly. The bending of the tips of small hysteresis loops indicate that the output transformers and chokes of audio-frequency amplifiers do introduce appreciable distortion in the form of odd harmonics even when operating at a small A.C. magnetization and that this distortion increases with a D.C. magnetization. For reduction of these distortions it is not only necessary that the cores of these transformers operate at an A.C. flux-density much smaller than the usual 10, 000 gauss for power transformers, but that the no-load current be considerably smaller compared to the load current. In case there is a D.C. magnetization produced due to the flow of a D.C. current in one of the windings, an air gap must be introduced and it is recommended that it may profitably be somewhat greater than what may be necessary to secure the maximum inductance.

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